

LETTER TO THE EDITOR

Two branches of neutron stars - reconciling a $2M_{\odot}$ pulsar and SN1987A

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ABSTRACT

Aims. The analysis of SN1987A led Brown and Bethe (1995) to conclusion, that the maximum mass of cold neutron stars is low, $M_{\max} \approx 1.5 M_{\odot}$. Such a low M_{\max} , due to a kaon condensation in the stellar core, implies collapse of a too massive deleptonized protoneutron star into a black hole. This would naturally explain the lack of a neutron star in the SN1987A remnant. On the other hand, recent evaluation of mass of PSR J0751+1807 gives $M_{\max} \gtrsim 2 M_{\odot}$. This contradicts the original Bethe-Brown model, but can be reconciled within scenarios proposed in the present Letter.

Methods. We consider two types of dense matter models with high-density softening, due to a transition from a non-strange N-phase of matter to a strangeness carrying phase S: kaon condensation and deconfinement of quarks. Two scenarios of neutron star formation in stellar core collapse are considered. In the first scenario, realized in sufficiently hot and dense supernova cores, nucleation of an S-phase is sufficiently rapid so as to form an S-phase core, and implying $M_{\max} = M_{\max}^S \approx 1.5 M_{\odot}$. In the second scenario, nucleation of the S-phase at neutron star birth is too slow to materialize, and the star becomes cold without forming an S-phase core. Then, stellar mass can increase via accretion, until central density ρ_{crit} is reached, and the S phase forms. This N branch of neutron stars ends at $M = M_{\text{crit}}$.

Results. We select several models of N-phase satisfying the necessary condition $M_{\max}^N \gtrsim 2 M_{\odot}$ and combine them with models of kaon condensation and quark deconfinement. For kaon condensation, we get $M_{\text{crit}} \approx M_{\max}^S \approx 1.5 M_{\odot}$, which is ruled out by PSR J0751+1807. On the contrary, for the EOSs with quark deconfinement we get $M_{\text{crit}} \approx M_{\max}^N \gtrsim 2 M_{\odot}$, which reconciles SN1987A and PSR J0751+1807.

Key words. dense matter – equation of state – stars: neutron – supernovae: SN1987A

1. Introduction

The actual equation of state (EOS) is one of the secrets of neutron stars. Uncertainties of our models of neutron star cores at density exceeding significantly the normal nuclear density $\rho_0 = 2.7 \times 10^{14} \text{ g cm}^{-3}$ results in the ignorance about the EOS at, say, $\rho \gtrsim 2\rho_0$. An important characteristics of an EOS model is the maximum allowable mass of neutron stars that it predicts, M_{\max} . Mathematically, M_{\max} is a functional of the EOS, $M_{\max} = M_{\max}[P(\rho)]$. Rotation increases M_{\max} , but even for highest observed pulsar frequency this increase is $\sim 3\%$ and can therefore be neglected (see, e.g., Haensel et al. 2007).

Measured neutron star masses increase in number and in precision (for a recent review, see Haensel et al. 2007). Let us denote the largest measured neutron star mass by M_{obs}^{\max} . To be consistent with observations, an EOS should yield $M_{\max} > M_{\text{obs}}^{\max}$. Therefore, higher the value of M_{obs}^{\max} , stronger the constraint on the stiffness of the EOS of neutron star core. Masses significantly higher than $1.4 M_{\odot}$ were measured in some pulsar - white dwarf binaries, the largest of them was $2.1 \pm 0.2 M_{\odot}$ for PSR J0751+1807 (Nice et al. 2005). Clearly, $M_{\max} \gtrsim 2 M_{\odot}$ necessitates a stiff EOS.

This conclusion seems to be in conflict with a puzzling absence of a neutron star in the SN1987A remnant. Indeed,

Bethe & Brown (1995) concluded, that $0.075 M_{\odot}$ of the radioactive ^{56}Ni produced by SN1987A together with other characteristics of this SN and of the presupernova star, imply an upper bound $M_{\max} \approx 1.5 M_{\odot}$. Such a low value of M_{\max} has been attributed by Bethe & Brown (1995) to the kaon condensation in neutron star core, and was also used as an argument for a large number of low-mass black holes in the Galaxy (Brown & Bethe 1994).

In the present Letter we show that a low upper bound $\approx 1.5 M_{\odot}$ from SN 1987A, and a high lower bound $\gtrsim 2 M_{\odot}$ from the mass of PSR J0751+1807, can be reconciled if they refer to two different branches of neutron stars, formed in different evolutionary scenarios. The low- M_{\max} branch consists of configurations with superdense strangeness-carrying (S) cores and was assumed to be formed in a collapse of massive stars ($20 - 30 M_{\odot}$ on the main sequence). The S-phase, characterized by a significant strangeness per baryon, is assumed to nucleate at sufficiently high temperature and density in a newborn neutron star. The S phase core remains in equilibrium with a non-strange (or a weakly strange) N-phase envelope. Such configurations form an S-branch of neutron stars, with $M_{\max}^S \approx 1.5 M_{\odot}$. On the other hand, the configurations laying on the high- M_{\max} branch are assumed to be initially formed as low-mass N-phase stars, and reached their present state by accretion of matter in a long-living close binary system. Such

stars can nucleate the S-phase only after reaching a critical mass $M_{\text{crit}} \gtrsim 2 M_{\odot}$: massive neutron stars with white dwarf companions were formed in such a way. The notion of M_{crit} as a maximum mass for a branch of neutron stars, metastable with respect to formation of a quark core, was recently studied in detail by Bombaci et al. (2007) (see also Bombaci et al. 2004). We give specific examples of dense matter models with N-S phase transition, and we show, that the original proposal of Bethe & Brown (1995) where the S-phase resulted from kaon condensation fails to produce a sufficiently high M_{crit} . However, the Bethe & Brown (1995) bound from SN1987A can be reconciled with $2 M_{\odot}$ neutron stars, provided they could follow different formation and evolution tracks, proposed in the present Letter.

In Sect. 2 we briefly describe the EOSs involving kaon condensation and quark deconfinement. Two branches of neutron stars, for kaon-condensed and quark-matter cores, are constructed in Sect. 3. Astrophysical scenarios leading to two neutron star branches are summarized in Sect. 4.

2. EOSs with phase transitions: stable and metastable branches

2.1. Kaon condensation

Interaction with nucleons can greatly reduce the energy of a single K^- in nuclear matter, ω_K . Consequently, kaons could appear in nucleon matter, forming a Bose-Einstein condensate (Kaplan & Nelson 1986; for review see Ramos et al. 2001). In what follows, we consider kaon condensation in neutron star cores composed of neutrons, protons, electrons, and muons ($npe\mu$ matter). Nucleons are described using two versions of the relativistic mean-field model with scalar self-coupling (Glendenning & Moszkowski 1991, Zimanyi & Moszkowski 1990). Coupling of kaons to nucleons is described by the models of Glendenning & Schaffner-Bielich (1999), the crucial parameter being the depth of the potential well of kaons in symmetric nuclear matter at saturation point, U_K^{lin} . In what follows we will measure temperature T in MeV ($T[\text{MeV}] = 0.8617 \cdot T[\text{K}]/10^{10}$). We will consider two basic cases. The low T case corresponds to $T < 1$ MeV. Such conditions prevail in the cores of single neutron stars older than one day, as well as in the neutron stars accreting matter in binary systems. The high T case with $T \approx 50$ MeV can be realized in the central core of newborn neutron star during 10 s just after the deleptonization.

Let us first assume $T < 1$ MeV. All core constituents are strongly degenerate. The $npe\mu$ matter becomes unstable with respect to spontaneous formation of kaons at density ρ_{crit} , at which the electron Fermi energy $\mu_e = \omega_K$. Then the density of kaons grows till the equilibrium between the normal N phase of dense matter and the kaon-condensed S phase is reached. Two possibilities of the coexistence of the N and S phases should be contemplated. The coexistence of the pure N and S phases takes place at a well defined pressure, P_0 , and is associated with a density jump $\rho_N \rightarrow \rho_S$, or it occurs via a mixed-phase state in the pressure interval $P_{m1} < P < P_{m2}$. Whether the phase transition takes place at a constant pressure, or via a mixed state, depends on the poorly known surface tension at the N-S interface, and on the scenario of formation of a kaon condensed core. An example of baryon chemical potential vs. pressure for different phases is shown in Fig. 1, and the parameters as-

Table 1. Densities ρ_N and ρ_{crit} and maximum neutron star masses. *Upper panel: EOSs with kaon condensation.* The first two letters refer to the nucleon EOS (ZM - Zimanyi & Moszkowski 1990; GM - Glendenning & Moszkowski 1991) and the last two denote the kaon condensation model (GS - Glendenning & Schaffner-Bielich 1999). The three digit number gives the value of $-U_K^{\text{lin}}$. *Lower panel: EOSs with quark deconfinement.* Letters denote the nucleon EOS: APR - Akmal et al. (1998); GN - case 5 in Glendenning (1985). Quark matter is described within the MIT Bag Model (see, e.g., Farhi & Jaffe 1984). First number gives the value of the bag constant (in MeV fm^{-3}), while the second number gives the mass of the s quark (in MeV). In all cases the QCD coupling constant $\alpha_s = 0.2$. For further explanations see the text.

model	ρ_N^a	ρ_{crit}^a	$M_{\text{max}}^S{}^b$	M_{crit}^b
ZMGS100	8.78	9.14	1.57	1.55
GMGS130	8.13	8.85	1.42	1.53
APR.100.150	10.3	20.1	1.57	2.13
APR.90.200	11.0	19.7	1.62	2.13
GN.100.150	5.06	22.0	1.48	2.145 ^c
GN.90.200	5.14	20.9	1.51	2.14

^a in $10^{14} \text{ g cm}^{-3}$, ^b in M_{\odot} . ^c Here $\rho_{\text{crit}} > \rho_{c,\text{max}}$ and therefore $M_{\text{crit}} = M_{\text{max}}^N$.

sociated with the $N \rightarrow S$ transition models are given in Table 1. In the high- T case the inclusion of the T dependence of the EOS is mandatory. Moreover, high T makes the kaon condensation weaker (Pons et al. 2000). However, the thermal effects do not affect our conclusions regarding cooled neutron stars.

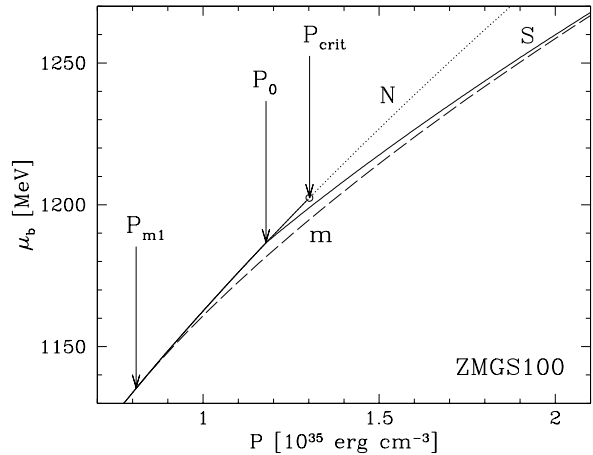


Fig. 1. Baryon chemical potential $\mu_b = (\mathcal{E} + P)/n_b$ (\mathcal{E} - energy density, n_b - baryon number density) vs. pressure. $T = 0$ approximation is assumed, calculations for the ZMGS100 model of kaon condensation in $npe\mu$ matter (see Table 1). Dotted line - unstable N phase. Long dashes - mixed phase.

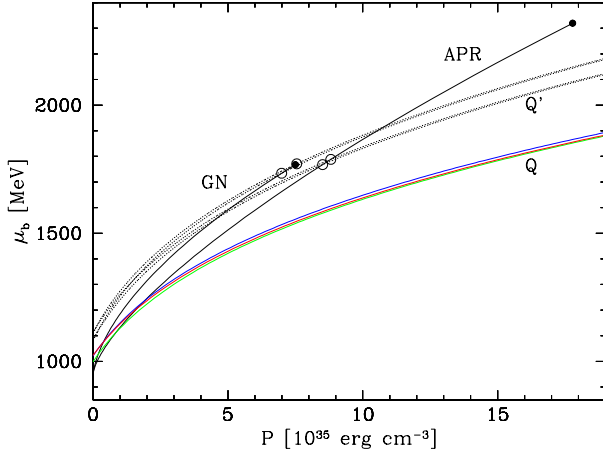


Fig. 2. (Color online). Baryon chemical potential vs. pressure. Solid lines - two models of the $npe\mu$ matter, filled circles - maximum central density of neutron stars built of the N phase. Open circles - first-order phase transition to non-strange quark matter. Parameters B , α_s , and m_s of quark matter are the same as in Table 1.

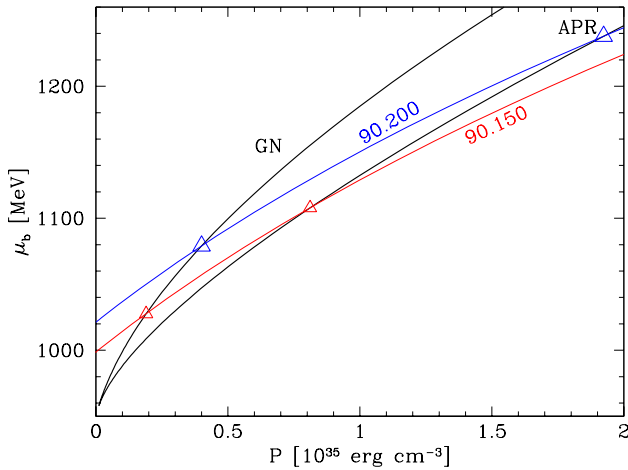


Fig. 3. (Color online). Phase transitions $N \rightarrow Q$ to three-flavor quark matter in beta and strangeness equilibrium, at $T = 0$. APR and GN models of the N phase are used. Models of Q phase are labeled by the values of B and m_s . In both cases $\alpha_s = 0.2$. Open triangles - first-order phase transition to quark matter.

2.2. Deconfinement of quarks

Here the N phase is again the $npe\mu$ matter. Quark deconfinement is a strong interaction process. Therefore, it produces the non-strange quark plasma of the u and d quarks, with the same lepton fractions (per baryon) as in the N phase. This quark plasma state will be called Q' . The transition $N \rightarrow Q'$ takes place at some P_{crit} . Then, weak interactions convert nearly half of the d quarks into the s ones, producing the equilibrated uds quark plasma state Q . The quark phases Q' and Q are described using the MIT Bag model, with parameters given in Table 1. In all cases, we use the same QCD coupling constant $\alpha_s = 0.2$.

In Fig. 2 we plotted baryon chemical potential $\mu_b = (\mathcal{E} + P)/n_b$ versus pressure P , for two models of the N phase,

and several models of the Q' and Q phases of quark matter. At given P , the Q' phase has the same lepton fractions, $x_e = n_e/n_b$ and $x_\mu = n_\mu/n_b$, as the beta equilibrated N phase. As far as the quark matter phases are concerned, some generic features can be pointed out. For a given model of the N phase, and a fixed value of α_s , higher value of B gives a higher value of P_{crit} . On the other hand, for a given pair B, α_s , the pressure P_{crit} for the softer EOS (APR) is higher than for the stiffer one (GN). After strangeness and beta equilibration, the phase transition pressure, P_0 , is much lower than P_{crit} . The dependence of P_0 on the quark matter model parameters is quite strong, as seen in Fig. 3.

For $T < 1$ MeV all dense matter phases are strongly degenerate, and phase transition parameters can be very well approximated by the values obtained at $T = 0$. An example of pressure dependence of the chemical potentials, and resulting phase transition points, is given in Fig. 2. Nucleation of the Q' phase is realized there in the quantum regime via energy barrier penetration, at the pressure slightly larger than P_{crit} (see Bombaci et al. 2007 and references therein).

For $T \approx 50$ MeV, transition to the Q' phase occurs at significantly lower density than $\rho_{\text{crit}}(T = 0)$ (see, e.g., Lugones & Benvenuto 1998). Moreover, at $T \gtrsim 50$ MeV thermal nucleation of the Q' phase, via jumping over the energy barrier separating the N and Q' states, is very efficient. Additionally, at such a high T a Boltzman gas of lightest hyperons is present (even if it is absent at $T < 1$ MeV). These thermal hyperons act as nucleation centers for the quark matter, for they add the s quarks to the Q' phase. A high T greatly accelerates $u + d \rightarrow s + u$ process, leading to a rapid strangeness equilibration associated with $Q' \rightarrow Q$.

3. Two branches of neutron stars

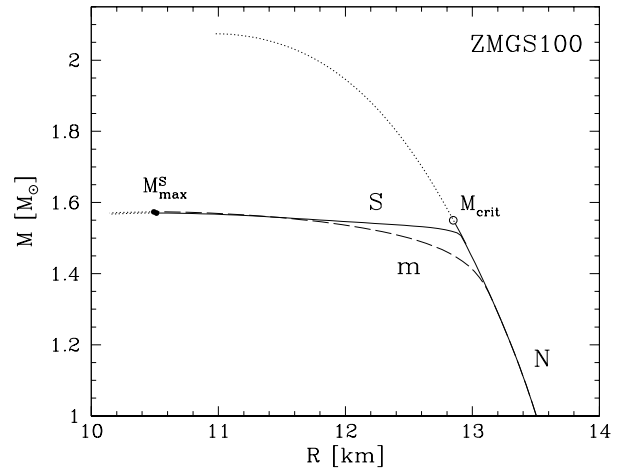


Fig. 4. Branches $M(R)$ for EOSs with kaon condensation. Configurations on the dotted lines are unstable. For further explanation see the text.

Let us start with kaon condensation. The $M(R)$ plots at $T < 1$ MeV, obtained by solving the Tolman-Oppenheimer-Volkov equations of hydrostatic equilibrium (see, e.g., Haensel et al. 2007), are shown in Fig. 4. The N-branch of cold stars, built exclusively of N phase, ends at $M_{\text{crit}} = M^N(\rho_c = \rho_{\text{crit}})$. There are two branches with S phase cores. The S branch consists of configurations with a pure S phase core, while configurations on the m branch have mixed-phase cores. However, as one can see, they both end at (nearly) the same maximum mass, denoted by M_{max}^S .

There are two basic formation scenarios. If a newborn hot neutron star did not nucleate kaon condensate, then after cooling it lies on the N branch. By accreting matter in a close binary system, such a neutron star can move upwards along the N branch, up to M_{crit} , and then collapses into a black hole (case GMGS130 in Table 1) or develops a kaon condensed core and settles on the S branch or m branch (case ZMGS100 in Table 1). However, in all cases the maximum mass $M_{\text{crit}} \approx M_{\text{max}}^S \approx 1.5 M_{\odot}$.

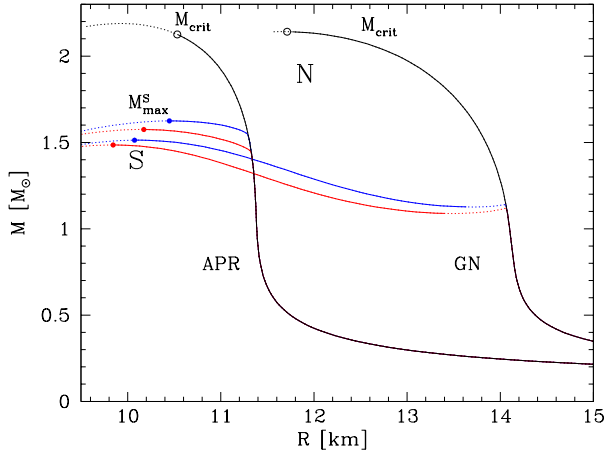


Fig. 5. (Color online) Branches $M(R)$ for EOSs with quark deconfinement phase transition (Table 1). Configurations on the dotted segments are unstable. Open circle: configuration of N phase with $M = M_{\text{crit}}$. Filled circle: limiting configuration with S phase core and $M = M_{\text{max}}^S$. For further explanation see the text.

Consider now the case of quark deconfinement. The $M(R)$ plots for several models of the N, Q' , and Q phases are displayed in Fig. 5. Two branches of neutron stars are clearly visible. The S branch shape, and in particular its initial point at central density $\rho_c = \rho_N$, are quite sensitive to the dense matter model. However, the maximum mass of the S branch, i.e. M_{max}^S , is quite independent of the dense matter model, $M_{\text{max}}^S \approx 1.5 M_{\odot}$. In our calculations, the quark cores of configurations on the S branch are made of pure quark matter, but we know from Alford et al. (2006), that the value of M_{max}^S , calculated for the mixed quark-nucleon cores, is to a very good approximation the same as for the pure quark-matter cores. The N branches end at $\rho_c = \rho_{\text{crit}}$, at $M_{\text{crit}} \gtrsim 2 M_{\odot}$. Let us stress that the N branch configurations with $M > M_{\text{max}}^S$ have no twins of the same mass on the S branch. Rather, they are “high mass siblings” of “low mass” neutron stars of branch S.

Consider a low T scenario. A newborn neutron star had, after deleptonization, central T and ρ too low to nucleate the Q' phase during some 10 s of extremal central conditions. After cooling, the star will lie on the N branch, Fig. 5, and can move upwards along this branch due to accretion.

The high- T scenario is different. We assume that during critical 10 s after deleptonization, central temperature $T \gtrsim 50$ MeV, and central density exceeds $\rho_{\text{crit}}(T)$. Consequently, Q' phase forms and transforms into the Q phase by strangeness-changing reaction. Two final states are then possible. Either neutron star settles on the S branch, Fig. 5, with maximum mass $M_{\text{max}}^S \approx 1.5 M_{\odot}$, or it collapses into a black hole if its mass $M > M_{\text{max}}^S$. If the star

settles on the S branch, further mass accretion can move it upwards along this branch. After reaching M_{max}^S , the star will collapse into a black hole.

4. Two scenarios resulting in two maximum masses

The original Brown-Bethe (BB) scenario involved kaon condensation in a deleptonized newborn neutron star, and predicted maximum mass of $1.5 M_{\odot}$ for cold neutron stars. The BB scenario applied to type II SNaE, originating from collapse of massive stars (main-sequence mass $20 - 30 M_{\odot}$). This scenario could explain the absence of neutron star in the SN1987A remnant and the production of $0.075 M_{\odot}$ of radioactive ^{56}Ni in that supernova. We have shown that even neutron stars that initially had no kaon condensed core, and increased their mass by accretion, could never exceed $M_{\text{crit}} \approx 1.5 M_{\odot}$; this would contradict recent measurements of neutron stars masses. We argue that the BB scenario could be saved, if kaon condensation, causing the softening of the EOS, is replaced by the quark deconfinement. Quark deconfinement might allow for two scenarios associated with two significantly different maximum masses. In the first one, neutron stars, born in core-collapse of massive stars ($20 - 30 M_{\odot}$), were sufficiently hot and dense after deleptonization to produce EOS-softening quark core, which resulted in $M_{\text{max}}^S \approx 1.5 M_{\odot}$; this was the case of SN1987A. However, there are also type II SNaE, resulting from the collapse of less massive stars, when a hot deleptonized neutron star has no quark core. This could be the case of SNaE produced by the electron-capture collapse of degenerate O-Ne-Mg cores of helium stars (van den Heuvel 2007 and references therein). After cooling, such neutron star could increase its mass by accretion in a long-lived binary system, up to $M_{\text{max}} \gtrsim 2 M_{\odot}$. This second maximum mass, characteristic of the normal (no quark core) neutron-star branch, is just a critical mass for nucleation of a low-strangeness quark matter. It is consistent with largest measured masses of pulsars with white dwarf companions.

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